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Photo-Induced Spin Dynamics in Semiconductor Quantum Wells

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Abstract We experimentally investigate the dynamics of spins in GaAs quantum wells under applied electric bias by photoluminescence (PL) measurements excited with circularly polarized light. The bias-dependent circular polarization of PL (P_{PL}) with and without magnetic field is studied. The P_{PL} without magnetic field is found to be decayed with an enhancement of increasing the strength of the negative bias. However, P_{PL} in a transverse magnetic field shows oscillations under an electric bias, indicating that the precession of electron spin occurs in quantum wells. The results are discussed based on the electron–hole exchange interaction in the electric field.

Keywords Photoluminescence · Spin transport · Exchange interaction

Introduction

Possibility of using information carried by the spin of the electron in electronic devices, in addition to its charge, has gained a lot of attention since the discovery of long spin lifetimes in semiconductor structures [1], leading to the growth of the field spintronics [1–3]. This may lead to new devices beyond well-established storage or memory applications, already implemented as giant magnetoresistance (GMR) read-heads and nonvolatile magnetic RAM (MRAM) [2].

One of the major hurdles in the development of spintronic devices has been the problem of efficiently injecting spin-polarized carriers into a semiconductor, transporting them over reasonable distances without spin-flipping and then detecting them. Much effort [3] has thus been spent in understanding the transport and dynamics of spins and the generation/injection and detection of spin currents in semiconductors. Generation of spin polarization usually means creating a nonequilibrium spin population. This has been achieved in various ways, e.g. by optical techniques, or by magnetic semiconductors or ferromagnetic contacts, with varying degrees of success [3]. Although the detection of spin current in semiconductors was previously been achieved mainly through optical methods [1], an electrical means of detecting spin current has been obtained recently [4–6]. Despite many efforts and substantial progress, a further major obstacle to the practical implementation of spintronics is the lack of a proper understanding of spin transport and dynamics in semiconductor-based heterostructures [3].

In this paper, we focus on spin dynamics in GaAs quantum wells (QWs) under applied electric bias by photoluminescence (PL) measurements excited with circularly polarized light [7–9]. We study the bias-dependent circular polarization of PL (P_{PL}) with and without magnetic field. The P_{PL} without magnetic field is found to be decayed with an enhancement of increasing bias. However, P_{PL} in a transverse magnetic field shows oscillations under an applied bias, indicating that the precession of electron spin occurs in QWs. The results are discussed by exploring the possible roles played in the observed phenomena.

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Experimental

The samples studied in the present investigation were GaAs double QWs (10 nm) separated by a thin (∼20 nm) $Al_{0.3}Ga_{0.7}As$ barrier. The samples were grown on the Si-doped GaAs substrate. For the application of the external bias (field normal to the heterostructure layers), the top surface of the sample was coated with a semitransparent electrode (Au). We excited the sample by circularly polarized ps pulses of a tunable Ti: sapphire laser with a repetition rate of 76 MHz and measured the PL both in zero magnetic field and in a magnetic field (5 T) aligned perpendicular to the growth axis of the structure (Voigt geometry) using a streak camera. The PL was excited directly to the exciton absorption band and was detected with the small long-wavelength shift to minimize the polarization losses [10, 11]. The exciting beam was directed perpendicular to the magnetic field direction, and the PL was detected in the backward direction. A schema of the experimental setup is shown in Fig. 1. All the measurements were done at liquid helium (LH) temperature by placing the samples in a cryostat. The degree of circular polarization (P_{PL}) was calculated by defining it as the ratio of the difference of the signals of the right and left circularly polarized PL to their sum.

Results and Discussion

The circularly polarized PL was studied as a function of the electric bias and of the external magnetic field. The PL was measured in the left and right circular polarizations under right circularly polarized excitation. In the absence of the magnetic field, the PL intensities with the same and opposite circular polarization for −2.5 V bias are shown in Fig. 2. Figure 3 shows the kinetics of the degree of circular PL polarization. As seen, the PL polarization kinetics of the QWs substantially depends on bias. In the absence of the bias (Fig. 3a), the kinetics of the P_{PL} has a small slow component with the decay time 1 ns dominated by a fast component characterized by the decay time below 0.1 ns, in consistence with other observations [12, 13]. When a

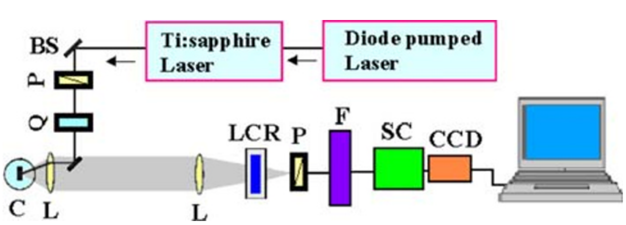

Fig. 1 A schema of the experimental setup (*BS* beam splitter, *P* polarizer, *Q* quarter wave plate, *L* lens, *LCR* liquid crystal retarder, *F* filter, *SC* streak camera). The sample was placed in a LH cryostat (C)

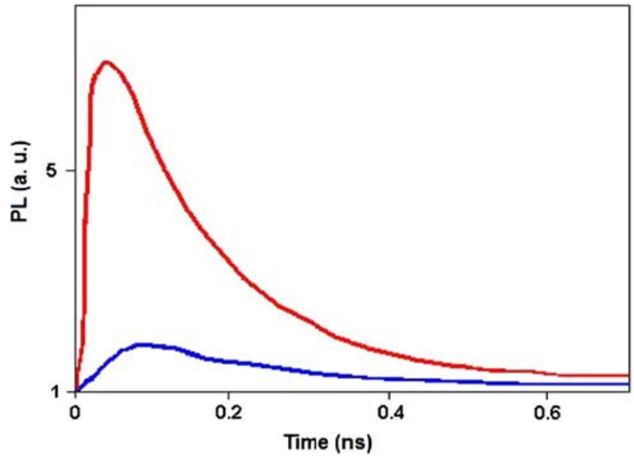

Fig. 2 PL intensities with the same (*red line*) and opposite (*blue line*) circular polarization at −2.5 V bias

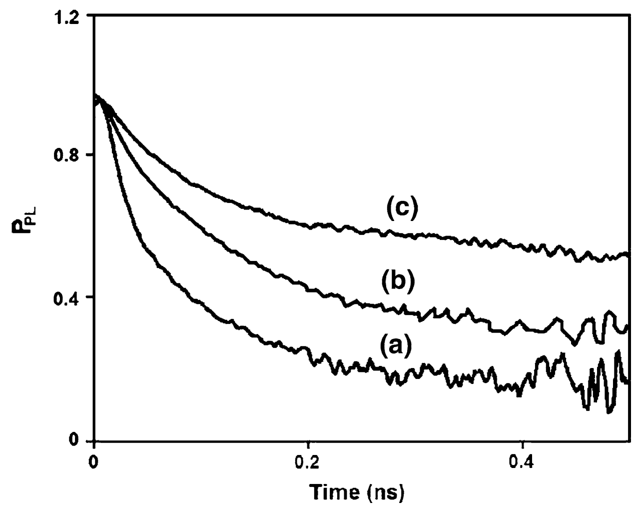

Fig. 3 Measured P_{PL} at **a** zero, **b** −1.5 V and **c** −2.5 V biases

negative bias is applied to the top electrode of the sample, the amplitude of the slow component increases and, for the applied bias, this component predominates.

One more mechanisms of the relaxation of the excitonic spin oriented by the light might be possible. Relaxation can result in the PL depolarization due to a flip of the exciton spin as a whole or independent flips of the electron and hole spins [14]. In the first case, the decay time of the P_{PL} is directly determined by the exciton spin relaxation rate [15]. If the carrier spins relax independently, the fast flip of the hole spin does not affect the P_{PL}. In this case, the decay of the P_{PL} is controlled by the relaxation of the long-lived electron spin. The above analysis reveals that the bias-induced changes in the polarized PL kinetics are related to transition from dynamics of the exciton spin to that of independent electron and hole spins. In the absence of the bias, the exchange coupling exceeds the spin–phonon interaction [16], and the main relaxation mechanism is given by the exciton spin flips, as mentioned above.

In the presence of the applied bias, the electric field reduces the electron–hole exchange coupling by spatially separating the charges, and as a result, the interaction of the hole spin with phonons becomes stronger than the exchange interaction. This leads to a breakage of the coupling between the electron and hole spins. As a consequence, the hole spin exhibits fast relaxation, while the electron spin holds its orientation, providing the slow component in the P_{PL} decay. The decay time as measured at -2.5 V is 1 ns, which agrees with the literature value [17].

Figure 4 shows the P_{PL} in the presence of the applied magnetic field for zero and -2.5 V bias. As can be seen, the effect of the bias on the polarized PL kinetics of the QWs appears to be more pronounced in the presence of the transverse H. For the -2.5 V bias, the polarization kinetics shows distinct oscillations symmetric with respect to the horizontal axis. An analysis of the P_{PL} dynamics in H gives additional evidence for the exchange interaction suppression in an external electric field. In the presence of the bias, the hole spin rapidly relaxes and its projection onto the direction of observation varies. Being uncoupled with the hole spin, the electronic spin may freely precess around the magnetic field direction. The projection of the electron spin onto the direction of observation oscillates in time with the Larmor frequency $\omega_L = g\mu_B H/\hbar$ [18], where μ_B is the Bohr magneton, g is the electron-g factor and $\hbar$ is the reduced Planck constant. The P_{PL} should oscillate between +1 (100%) and -1 with the same frequency [19] because, when the hole spin has no preferential orientation, this quantity is determined only by the projection of the electron spin.

As can also be seen from Fig. 4, the oscillation amplitude is initially equal to $\sim$0.8 and slowly decays with time.

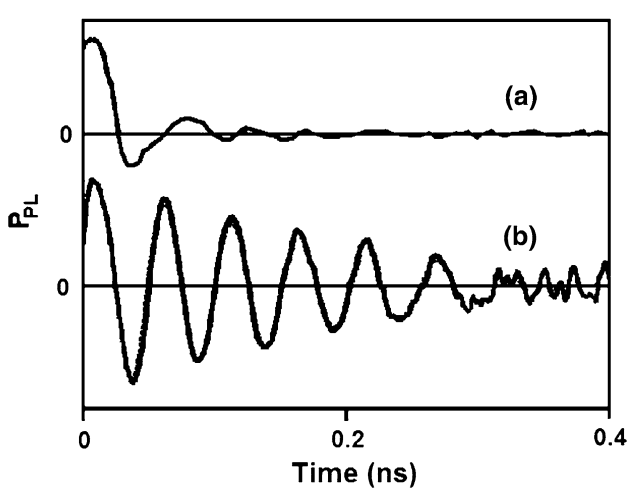

Fig. 4 P_{PL} in the presence of the magnetic field at **a** zero and **b** -2.5 V bias

The data can be fitted by the exponentially damping harmonic function $P_{PL} = P^0_{PL}\exp(-t/\tau)\cos\omega_L t$, which gives $\omega_L = 0.1$ THz and the decay time $\tau = 200$ ps for the -2.5 V bias and $H = 5$ T. The obtained oscillation frequency ω_L corresponds to the value $g = 22.7 \times 10^{-2}$. This agrees with the experimental as well as theoretical estimates of the transverse electron g-factor in GaAs QWs [20–22].

In the absence of the bias, there involves only the behaviour of the exciton spin as a whole. The H mixes the excitonic states, and as a result, the right circularly polarized light becomes capable of exciting several states. The kinetics of the polarized PL is controlled here by the interference of the states of the exciton fine structure split by the combined action of the magnetic field and exchange coupling induced by the external electric field [23, 24]. As Fig. 4a demonstrates, the P_{PL} varies with time in a rather complicated fashion of the PL polarization kinetics [25], reflecting superposition of the beats at several frequencies. From the above discussion, one can conclude that application of the bias to the QWs weakens the exchange interaction between the electron and hole spins.

Conclusion

The dynamics of spins in GaAs QWs under applied electric bias has been experimentally investigated by PL measurements. The bias-dependent P_{PL} with and without magnetic field was studied. The P_{PL} without magnetic field was found to be decayed with an enhancement of increasing negative bias. However, P_{PL} in a transverse magnetic field showed oscillations under an applied bias. The oscillation amplitude was found to be increased with increasing the strength of the bias. The results were discussed based on the electron–hole exchange interaction in the electric field.

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